Combining Swarm, GRACE-FO and Sentinel for topside electron density estimation

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Swarm, GRACE-FO and Sentinel

- Swarm: 470km (A/C), 520km (B), $87.4°$(A,C), $88°$(B) inclination,slowly drifting in local time
- GRACE-FO (GC, GD): 500 km, $89°$ inclination, slowly drifting in local time
- Sentinel 1A/1B (S1A, S1B): 693 km, $98.18°$ inclination, sun-synchronous $\sim$ 6/18 LT
- Sentinel 2A/2B (S2A, S2B): 786 km, $98.5°$ inclination, sun-synchronous $\sim$ 10/22 LT
- Sentinel 3A/3B (S3A, S3B): 814 km, $98.65°$ inclination, sun-synchronous $\sim$ 10/22 LT
- Near future: COSMIC-2 to increase coverage in the equatorial regions ($24°$ inclination)

GNSS TEC and Biases

Code:

$$sTEC \approx \frac{f_1^2 f_2^2}{f_1^2 - f_2^2}(P_1 - P_2 + B_{sat} + B_{rec} + B_{multipath})$$

Phase:

$$sTEC \approx -\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}(L_2 - L_1 + N_1\lambda_1 - N_2\lambda_2 + B_{PCV})$$

N_1, N_2 ambiguities, B_{PCV} Phase center variation, $B_{multipath}$ multipath bias, $B_{sat,rec}$ satellite/receiver P1-P2 bias. f_1, f_2 are the carrier phase frequencies and λ_1, λ_2 the coresponding wavelengths.

- B_{sat} known (IGS, zero mean)
- B_{rec} needs to be estimated
- Code leveling usually used for LEO's
- Multipath maps need to be estimated

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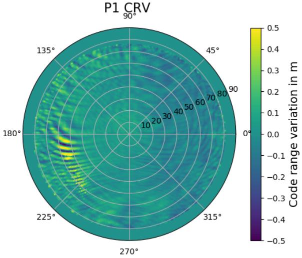
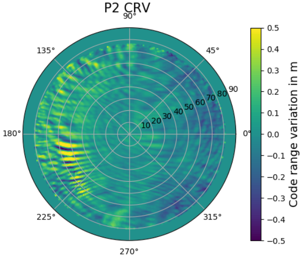
Multipath Estimation

Using the multipath linear combinations for each clean (no cycle-slip or outlier) phase arc:

$$M_{P1} = P_1 - L_1 + 2 \cdot (f_2^2/(f_2^2 - f_1^2)) \cdot (L_1 - L_2)$$
$$M_{P2} = P_2 - L_2 + 2 \cdot (f_1^2/(f_2^2 - f_1^2)) \cdot (L_1 - L_2)$$

Sentinel-1A:





Estimated using leveling and stacking for each phase arc individually and subsequently combined through least-squares for offset calibration.

Model formulation

- Epstein layer below 1000 km
- Exponential decay above 1000 km
- Tracing along magnetic field lines using apex coordinates. Layer profile functions are applied along magnetic field lines.
- Mixing in relation to apex height

Formulation using the max. electron density N_m at height h_m, and the scale height H

$$Ne = \begin{cases} 4 \cdot N_m \cdot \frac{e^{z_{bot}(h)}}{(1+e^{z_{bot}(h)})^2} & \text{for h} \leq 1000km \\ 4 \cdot N_m \cdot \frac{e^{z_{bot}(1000)}}{(1+e^{z_{bot}(1000)})^2} \cdot e^{-z_{top}(h)} & \text{for h} > 1000km, \end{cases} \tag{1}$$

where $z_{bot}(h) = \frac{h-h_m}{H_{bot}}$ and $z_{top}(h) = \frac{h-1000}{H_{top}}$.

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Representation

- Nm harmonic expansion at 80 km, degree/order 15
- H_{bot} harmonic expansion at 80 km, degree/order 15
- H_{top} harmonic expansion at 1000 km, degree/order 15
- h_m set to 350 km for compatibility with CODE Ionosphere maps

The reference altitudes need to be set at the lower bottom of the layer since field lines may only reach limited altitudes. The reference is taken from the location of the footprint of the coordinate at reference altitude.

Magnetic latidtude and magnetic local time are selected as coordinate system.

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Mixing condition

To ensure continuity at the magnetic equator a mixing condition is formulated:

$$N_e = \delta N_e^{north} + (1 - \delta) N_e^{south}, \tag{2}$$

where

$$\delta = \begin{cases} (\frac{h_{apx} - h}{h_{apx} - h_{ref}} + 1)/2 & \text{if Mlat} > 0 \\ 1 - (\frac{h_{apx} - h}{h_{apx} - h_{ref}} + 1)/2 & \text{else} \end{cases} \tag{3}$$

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Observations and adjustment

- Model parameters estimates for 3 h time windows
- Main Input: Swarm A,B,C, GRACE C/D (Follow On), Sentinel 1A,1B,2A,2B,3A,3B sTEC, reduced to 60s sampling
- Auxiliary Input: Calibrated Ne from Swarm Langmuir probes, Global Ionosphere Maps (GIM) provided by the Center for Orbit Determination Europe (CODE). Gridded vTEC extracted.

Parameters to be estimated:

- N_e, H_{bot}, H_{top}: 3x125 par.
- Phase wise biases due to Code noise and probably unstable receiver bias (~ 400 par.)
- Leveling of absolute offset for CODE TEC map (1 par.).

~ 775 unknowns

Parameter Adjustment

For parameter adjustment a batch least squares approach is applied. Since the model provides electron density, sampling along the line of sight and numerical integration needs to be applied.

$$\|\mathbf{L} \cdot \mathbf{D} \cdot \mathbf{x} - \mathbf{y}\| \rightarrow min. \tag{4}$$

Where $\mathbf{L}$ is the integration Operator, $\mathbf{D}$ evaluates the density at the sampled points, $\mathbf{x}$ contains the model parameters and $\mathbf{y}$ the observations. Due to the sampled points the dimension of $\mathbf{D}$ is approximately $20 \cdot n_{obs} \times n_par$ and almost fully populated. The integration matrix $\mathbf{L}$, however, is sparse.

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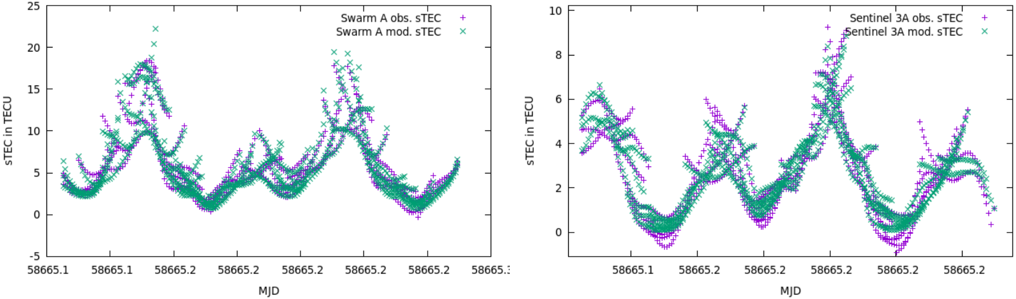
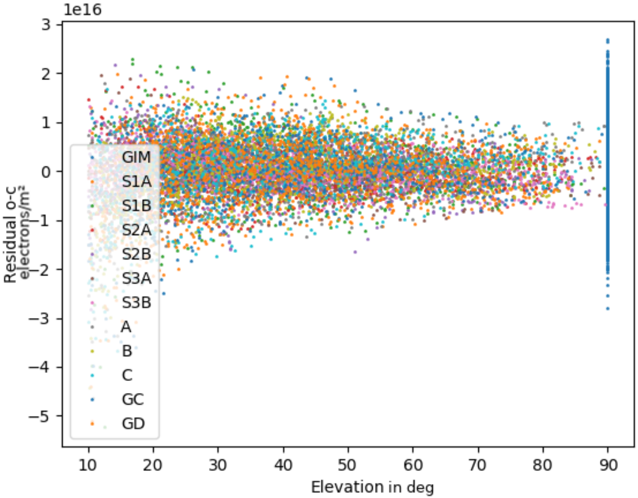
Comparison between modelled sTEC and observed sTEC

Modelled and observed sTEC values for the lowest satellite Swarm A and the highest satellite Sentinel 3A. The correlation coefficient between observed and modelled sTEC values is 0.986 for Swarm A and 0.981 for S3A



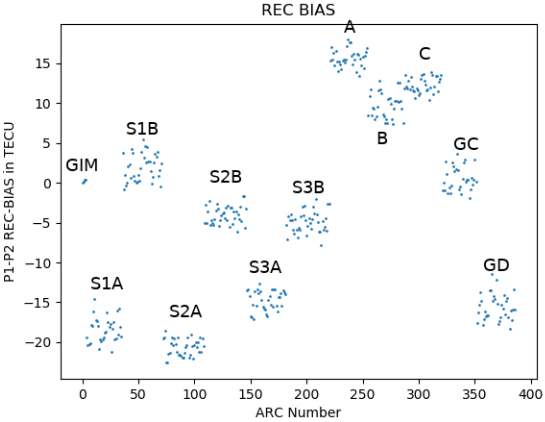
Elevation dependent residuals

Post fit residuals. The vertical line comes from the global ionosphere map, where only vertical TEC is extracted.



Receiver/Leveling Biases

A P1-P2 Bias is computed for each connected phase arc. Even with mulipath removed, a significant scatter of a few TECU can be observed. Also leveling biases for the global ionosphere maps provided by CODE are estimated.



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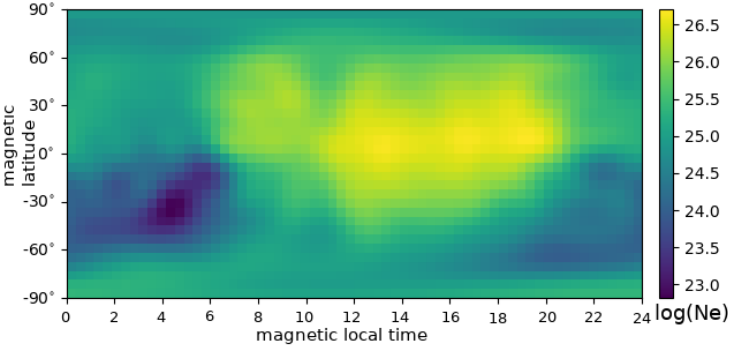
Electron Density

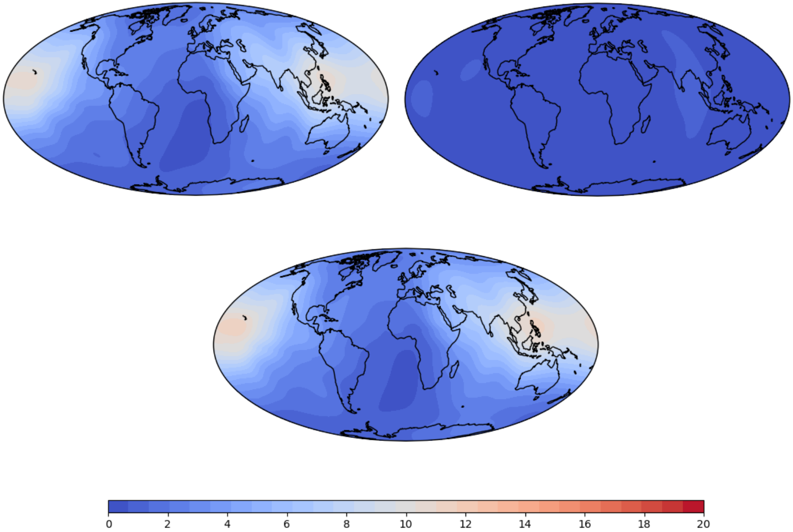
N_m estimated at 350 km at the footprint coordinates at 80 km from where it is projected to 350 km. Please note that field-lines near the equator at 80 km do not reach h_{max} (1/7/2019, 3:00 UT).



The unit of Ne is $electrons/m^3$

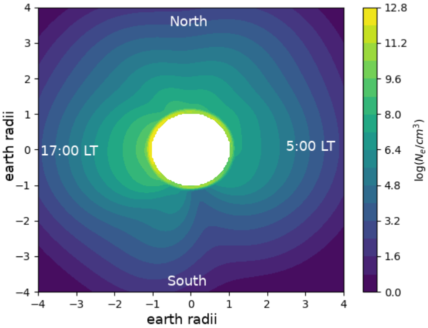
Ne integrated over different altitudes

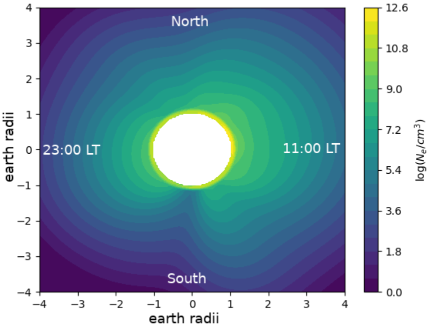
Example of TEC from 90 km-1000 km(left), from 1000 km-20.000 km (right) and combined (bottom). 1/7/2019, 3:00 UT



North/South slices with fixed local time

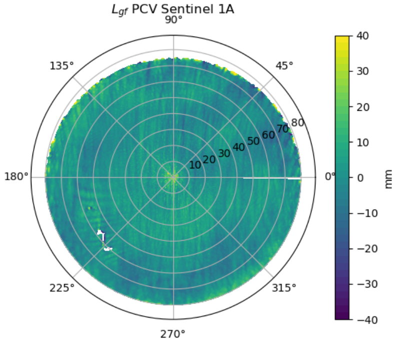
The three-dimensional nature may be seen in north/south slices of electron density (1/7/2019, 3:00 UT). It is clearly visible that the ionized plasma extends further near 17:00 LT or 11:00 LT (dayside) compared to 5:00 LT or 23:00 LT. (nightside)





geometry-free phase center variation maps

Generated by stacking and averaging the differences between the model output and the observed sTEC values. 1 cm in L_{gf} corresponds to approximately 0.96 TECU. Example Sentinel 1A

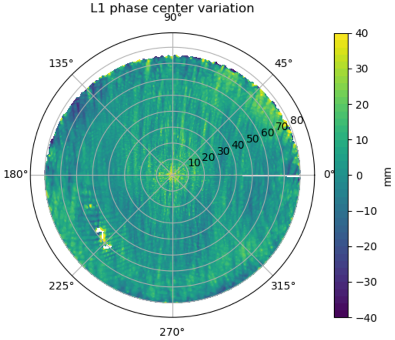


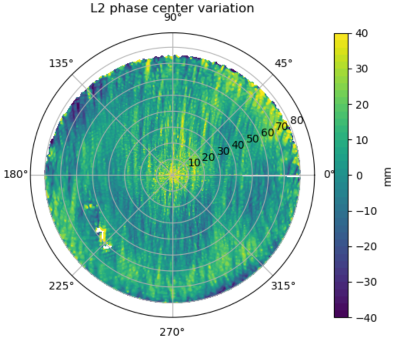
Example: Single frequency decomposition

$$\begin{aligned} L_{if} &= \frac{1}{f_1^2 - f_2^2}(f_1^1 L_1 - f_2^2 L_2) \\ L_{gf} &= L_1 - L_2 \end{aligned} \Leftrightarrow \begin{aligned} L_1 &= L_{if} - \frac{f_2^2}{f_1^2 - f_2^2} L_{gf} \\ L_2 &= L_{if} - \frac{f_1^2}{f_1^2 - f_2^2} L_{gf} \end{aligned} \tag{5}$$

When ionosphere-free and geometry-free linear combination available.

Example: Sentinel 1A





Conclusion / Outlook

- Plasmaspheric TEC can reach several TECU. However, it is very small during solar min.
- Sentinel, Swarm and GRACE-FO satellites provide a good basis, however, local time fixed or only slowly drifting.
- P1-P2 Receiver bias can vary depending on the phase arcs (few TECU).
- COSMIC-2 will help to obtain more observations from different local times in the equatorial region.
- Combined estimation with other LEO's to obtain consistent TEC at different altitudes was demonstrated.
- Geometry-free PCV maps can be estimated by analyzing post-fit residuals. These maps may in turn be used in combination to ionosphere-free PCV maps to derive single frequency PCV maps

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